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NUMERICAL SIMULATION OF SLIGHT DIRECTION CHANGES IN TWO-PHASE FLOWS USING A SLUG TRACKING MODEL

Carlos L. Bassani, carloslbassani@hotmail.com
Marco G. Conte, mg_conte@hotmail.com
Victor E. L. Parra, victorllantoy@gmail.com
César D. P. Medina, cesar.perea.medina@gmail.com
Cristiane Cozin, criscozin@yahoo.com.br
Fausto Arinos de A. Barbuto, fausto_barbuto@yahoo.ca
Rigoberto E. M. Morales, rmorales@utfpr.edu.br

LACIT/PPGEM/UTFPR, Av. Sete de Setembro 3165, CEP. 80230-901, Curitiba-PR-Brasil

Abstract. *Slug flow in pipes is a quite common flow pattern occurring in many industrial applications, most notably in the transportation of two-phase mixtures of oil and natural gas in offshore pipelines. The slug flow pattern is characterized by intermittent liquid slugs and elongated bubbles, whose lengths and velocities change in space and time. Hilly terrain effects influence flow parameters due to slight direction changes on the sea floor, making slugs to grow or generating new ones. These changes affect the pressure drops and are paramount in the design of production facilities. The present work introduces a mathematical model for the liquid accumulation due to horizontal-to-slightly inclined direction changes, analyzing only the slug growth. The aforementioned model attempts to describe the phase fraction changes in the liquid slug and in the elongated bubble and is coupled to a lagrangian slug tracking model for the prediction of hydrodynamic parameters. The results were compared to experimental data, and a good agreement has been obtained.*

Keywords*: two-phase flow, intermittent flow, hilly terrain, slug tracking*

1. INTRODUCTION

The slug flow pattern is characterized by the alternate flow of an elongated bubble and a liquid slug, which together constitute a slug unit. All parameters of the slug unit change in space and time, and their accurate prediction is central, for instance, in the design of oil and natural gas transportation facilities that are common to the petroleum industries around the world. Therefore, the development of reliable mathematical models for the simulation of slug flows has been a topic of research during the last decades.

Early studies used the concept of the unit cell, as proposed by Wallis (1969). Dukler and Hubbard (1975) and Fernandes *et al.* (1983) proposed unit cell models to predict hydrodynamic behaviour for horizontal and vertical flows, respectively. Later, Taitel and Barnea (1993) presented a more general approach for horizontal, vertical and inclined pipes. These models are called stationary models and consider that slug and bubbles repeat in space and time. They can accurately calculate the average bubble and slug lengths and the pressure drop in the pipe, but do not capture the inherent intermittence of the slug flow. November

Therefore, transient models to capture this particular feature of the phenomenon were developed. One of these models used to describe the intermittent flow is the slug tracking model, which encompasses mass and momentum balance equations in deformable control volumes from a frame of reference moving along with the unit cell. The early slug tracking models were able to merely simulate the movement of the bubbles by displacing the whole unit cell with the bubble translational velocity (Barnea and Taitel, 1993). Later, Taitel and Barnea (1998) presented an evolution of their previous work considering the gas compressibility effect. Ujang *et al.* (2006) presented an approach based on mass conservation equations for each unit cell, but neglected the compressibility of both phases. Recently, Rodrigues (2009) performed mass and momentum balances for separated control volumes in the slug and the bubble, considering ideal gas and incompressible liquid.

The previously mentioned models are capable of simulating horizontal, inclined and vertical flows, but do not consider the slight direction changes that frequently occur in the petroleum transportation due to the sea floor topology. These direction changes affect the flow behaviour, giving rise to the so-called hilly terrain effect. The gravitational force and the difference between the fluid densities cause liquid accumulation in low elbows, and slug growth or slug generation phenomena may happen depending on the liquid and gas superficial velocities, as pointed out by Al-Safran *et al.* (2005). Zheng *et al.* (1994), who modelled this liquid accumulation in a low elbow. More recently, Conte *et al.* (2011) coupled Zheng *et al.* (1994) model to Rodrigues (2009) slug tracking model. Gravitational force also changes the elongated bubble shape, as reported by Taitel and Barnea (1990), and the bubble acceleration in the inclined section causes the break-up of the bubble rear, thus dispersing small bubbles into the slug and changing phase fractions in the unit cell. Barbosa Filho (2010) modelled these phase fraction changes for vertical-ascendant to horizontal flows.

It is important to note that main changes in slug flow due to the hilly terrain effect occur in the elbow and the consequences propagate downstream. With that in mind, the present work introduces a model to predict the liquid accumulation in a low elbow for horizontal to slightly inclined flows and couples it to Rodrigues (2009) slug tracking model. Due to the model sensibility to phase fractions upstream and downstream the elbow, this phenomenon is also considered. Only the slug growth case is analyzed.

2. MATHEMATICAL MODEL

The mathematical one-dimensional model consists of an integral analysis of the mass and momentum balance equations, applied to each component of the unit cell. The following hypotheses were assumed: (i) incompressible liquid (ii) ideal gas, (iii) negligible forces in the gas bubble, (iv) negligible axial variation of the pressure inside each bubble, (v) constant phase fractions in the unit cells that are not passing through the elbow and (vi) negligible gas momentum.

Conservation equations

Rodrigues (2009) performed mass and momentum balances for the unit cell:

$$U_{LSj-1} - U_{LSj} = \frac{dP_{GBj}}{dt}\left[L_{Bj}\frac{\left(1-R_{LBj}\right)}{P_{GBj}} + \frac{L_{Sj}}{2}\frac{\left(1-R_{LSj}\right)}{P_{GBj}} + \frac{L_{Sj-1}}{2}\frac{\left(1-R_{LSj-1}\right)}{P_{GBj-1}}\right] + \left(\frac{1-R_{LSj}}{R_{LSj}}\right)U_{DSj} - \left(\frac{1-R_{LSj-1}}{R_{LSj-1}}\right)U_{DSj-1} \quad (1)$$

$$P_{GBj} - P_{GBj+1} = \frac{\tau_{LBj+1}S_{LBj+1}L_{Bj+1} + \tau_{LSj}\pi D L_{Sj}}{A} + \left(R_{LSj}L_{Sj} + R_{LBj+1}L_{Bj+1}\right)\rho_L g sen\theta + \rho_L L_{Sj} R_{LSj}\frac{dU_{LSj}}{dt} \quad (2)$$

where P is the pressure, L is the length, U is the velocity, S is the wetted perimeter, τ is the shear stress, ρ is the fluid density, R is the phase fraction, A is the area, D is the pipe diameter, Θ is the pipe inclination angle and U_{DS} is the drift velocity. The subscripts LBj, LSj and GBj represent the liquid film, the liquid slug and the elongated bubble of the j^{th} unit cell, respectively.

Direction change model

The model was developed for direction changes from horizontal to slightly inclined pipes. The present work models the liquid accumulation in the elbow when the slug passes through it, taking into account the phase fraction change. The cases with slug generation were ignored, and the model was developed for slug growth cases only. The pressure of the unit cell which is passing through the elbow must be recalculated taking into account the part that has already physically changed its direction, although not numerically:

$$\Delta P_{GBj} = \rho_L g R_{LSj}\left(L_{S1j} sen\theta_1 + L_{S2j} sen\theta_2\right) + \rho_L g R_{LBj}\left(L_{B1j} sen\theta_1 + L_{B2j} sen\theta_2\right) \quad (3)$$

where the subscripts 1 and 2 refer, respectively, to the part of the unit cell that has not yet passed the elbow and the part that has already changed its direction, as seen in Fig. 1. Applying the mass balance to the liquid phase in the control volume of Fig. 1 when slug is passing through the elbow, the liquid volume accumulation in the elbow becomes:

$$\frac{d\forall_0}{dt} = \left(U_{LBj} A R_{LBj}\right)_1 - \left(U_{LBj} A R_{LBj}\right)_2 \quad (4)$$

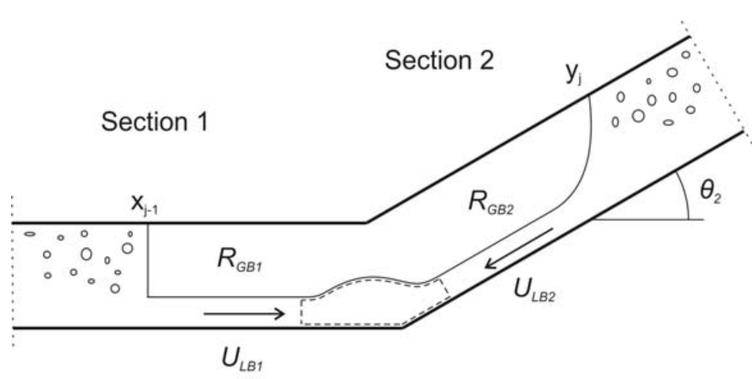

Figure 1. Liquid accumulation in an elbow when an elongated bubble passes by it.

The liquid velocity of the film is calculated by a mass balance for a rigid control volume that moves with the bubble translational velocity. The control volume is the region comprehended from half the film length to half the slug length. The mass balance results:

$$U_{LBj} = U_{Tj} + \frac{R_{LSj}}{R_{LBj}}\left(U_{LSj} - U_{Tj}\right) \tag{5}$$

Integrating Eq. (4) over time for a complete transit of the elongated bubble, dividing by the area and taking the phase fractions into account, the accumulated volume represents an accumulated length that will be added to the previous slug:

$$L_{acum} = \frac{\forall_0}{\left(R_{LSj-1} + R_{GBj} - 1\right)A} \tag{6}$$

After the unit cell passes the elbow, the phase fractions change due to the acceleration of the bubble, which yields part of its mass to the liquid slug in the form of dispersed bubbles. This characterizes mass transfer from the bubble that has just passed the elbow to the slug behind it. For the new slug liquid holdup, the Andreussi (1993) correlation is used:

$$R_{LS} = \frac{F_0 + F_1}{Fr_m + F_1}$$

where the coefficients F_0 and F_1 are calculated as $F_0 = \max\left(0; 2.6\left[1 - 2\left(0.025/D\right)^2\right]\right)$, $F_1 = 2400\left(1 - \sin\theta/3\right)Bo^{-3/4}$ and Fr_m and Bo are the Froude and Bond number, respectively. These numbers are calculated as $Fr_m = J/\sqrt{gD}$ and $Bo = gD^2\rho_L/\sigma$. The Andreussi (1993) correlation has been chosen because it takes into account the inclination angle of the pipe in coefficient F_1.

For the liquid film height, the differential equation presented by Taitel and Barnea (1990) is integrated using the rectangle rule:

$$\frac{\partial h_{LB}}{\partial x} = \frac{\dfrac{\tau_L S_{LB}}{A_L} - \dfrac{\tau_G S_{GB}}{A_G} - \tau_i S_i\left(\dfrac{1}{A_{GB}} + \dfrac{1}{A_{LB}}\right) + \left(\rho_L - \rho_G\right) g sen\theta}{\left(\rho_L - \rho_G\right) g\cos\theta - \dfrac{\rho_L\left(U_T - U_{LB}\right)\left(U_T - U_{LS}\right)}{R_{LB}^2}\dfrac{dR_{LB}}{dh_{LB}} - \dfrac{\rho_G\left(U_T - U_{GB}\right)\left(U_T - U_{GS}\right)}{R_{GB}^2}\dfrac{dR_{LB}}{dh_{LB}}} \tag{7}$$

The above equation describes the bubble shape and depends on the superficial velocities of the phases and geometrical parameters. Table 1 shows how to calculate geometrical parameters such as the angle ϕ (Fig. 2), the liquid fraction in the bubble R_{LB}, the gas (S_{LB}), liquid (S_{GB}) and interfacial (S_i) wetted perimeter in the elongated bubble region, and the cross sectional area the phases occupy, A_L and A_G. To achieve mass balance, integration of Eq. (7) must stop when:

$$\int_0^{L_{Bj}^N}\left(1 - R_{GBj}\right)dx = R_{LSj}^O L_{Sj-1}^O + \left(1 - R_{GBj}^O\right)L_{Bj}^O - R_{LSj}^N L_{Sj-1}^N \tag{8}$$

and the j^{th} bubble has just passed the elbow whereas the $(j\text{-}1)^{th}$ slug has not yet reached the elbow. This equation represents the dispersed bubble release from the elongated bubble that has already passed the elbow to the liquid slug behind it. The indexes O and N refer to old and new time steps, or just before and after recalculating the phase fraction and the bubble length.

The bubble front velocity is calculated as:

$$U_{Tj} = \left(C_0 U_{LSj} + C_\infty\sqrt{gD}\right)\left(1 + h\right) \tag{9}$$

where the coefficients C_0 and C_∞ are calculated according to Bendiksen (1984), which takes the inclination angle of the pipe into account. The coefficient h is the wake factor and can be calculated by Moissis and Griffith (1962) as $h = a_w \exp(-b_w L_S/D)$, where a_w and b_w are constants.

Table 1. Geometrical correlations for integration of Eq. (7).

$\phi = acos\left(1-2\dfrac{h_{LB}}{D}\right)$		$R_{LB} = \dfrac{\phi - 0.5sen(2\phi)}{\pi}$		$\dfrac{\partial R_{LB}}{\partial h_{LB}} = \dfrac{4sen(\phi)}{\pi D}$
$S_{LB} = \phi D$	$S_{GB} = \pi D - S_{LB}$	$S_I = D\,sen(\phi/2)$	$A_{LB} = AR_{LB}$	$A_{GB} = AR_{GB}$

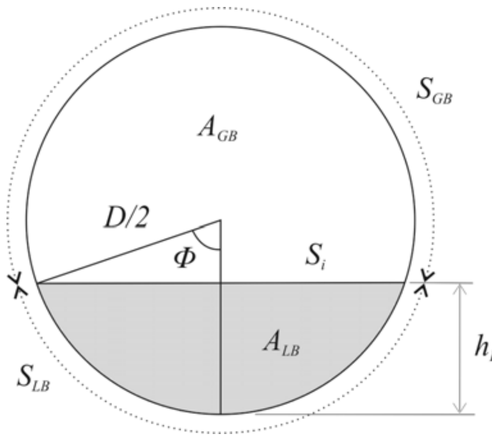

Figure 2. Definition of angle ϕ.

3. SOLUTION METHODOLOGY

Equations (1) and (2) are discretized in time using the semi-implicit Crank-Nicholson scheme, as follows:

$$
\begin{aligned}
&-U^N_{LSj-1} + P^N_{GBj}\left(\frac{2L_{Bj}R_{GBj}}{\Delta t P^O_{GBj}} + \frac{2L_{Sj}\left(1-R_{LSj}\right)}{\Delta t P^O_{GBj}} + \frac{2L_{Sj-1}\left(1-R_{LSj-1}\right)}{\Delta t P^O_{GBj-1}}\right) + U^N_{LSj} = U^O_{LSj-1} - U^O_{LSj} + \\
&+\left(\frac{2L_{Bj}R_{GBj}}{\Delta t} + \frac{L_{Sj}\left(1-R_{LSj}\right)}{\Delta t} + \frac{L_{Sj-1}\left(1-R_{LSj-1}\right)}{\Delta t}\frac{P^O_{GBj}}{P^O_{GBj-1}}\right) - 2\Delta U_{DSj}
\end{aligned}
\tag{10}
$$

$$
\begin{aligned}
&-P^N_{GBj} + \rho_L U^N_{LSj}\left(\frac{2R_{LSj}L_{Sj}}{\Delta t} + \frac{4C_{LSj}}{D}L_{Sj}U^O_{LSj}\right) + P^N_{GBj+1} = P^O_{GBj} - P^O_{GBj+1} + \\
&+\frac{2R_{LSj}L_{Sj}U^O_{GBj+1}\rho_L}{\Delta t} - 2\left(\Delta P_{Sj+1} + \Delta P_{Gj}\right)
\end{aligned}
\tag{11}
$$

where Δt is the time step, $U_{DSj} = (1-R_{LSj})U_{DSj}/R_{LSj} - (1-R_{LSj-1})U_{DSj-1}/R_{LSj-1}$, $\Delta P_{Gj} = \rho_L g sen\theta(R_{LSj}L_{Sj} + R_{LBj+1}L_{Bj+1})$, $\Delta P_{Sj+1} = 2C_{LBj+1}L_{Bj+1}\rho_L S_{LBj+1}U^2_{LBj+1}/\pi D^2$ and $C_f = 2\tau_f/(\rho_L U^2_f)$, $f = LB$ or LS. The superscripts N and O refer to the parameters evaluated in the new and old time steps, respectively.

Equations (10) and (11) are applied to all n unit cells in the pipe, resulting in a 2n-equation system, which is solved by the TDMA algorithm. For boundary conditions, the slug velocity of first cell ULS0 and the pressure of last bubble PGBn are needed. After pressure and slug velocity are calculated by the system, the unit cell borders are displaced.

When an elongated bubble passes the elbow, liquid is accumulated by Eq. (4). When the preceding slug reaches the elbow, the accumulated liquid is incorporated into this slug, which grows by L_{acum} (Eq. (6)). At the same time, the bubble shape differential equation (Eq. (7)) is integrated until convergence on the mass balance (Eq. (8)) is achieved and the new phase fractions and bubble length are then calculated.

Phase fractions are computed in a specific time step rather than continuously, so that computationally expensive calculations are avoided. This way, a unit cell is "frozen" in a time step and then the calculations are performed. Due to the slug and bubble length changes, the unit cell length also changes. Therefore, all other unit cells in front of this one need to be displaced taking these length variations into account. Numerical calculations sometimes lead to a decrease in the unit cell length, which is not predicted by the model, or to a unit cell length increase such as two other unit cells leaving the pipe. These two cases cause numerical instabilities and simulation interruption. Therefore, whenever they happen, the direction change is ignored for that specific unit cell and the simulation of the hydrodynamic parameters by Rodrigues (2009) model continues. Then, the direction change model runs again for the next unit cell.

4. RESULTS AND DISCUSSIONS

The proposed model is compared to experimental data obtained at UTFPR/LACIT. This experiment consists of an air-water mixture flowing in a horizontal-to-slightly inclined 1-inch (0.0254 m) pipe with 3°, 5° and 7° inclination angles. The geometrical parameters of the pipe are shown in Table 2. Table 3 shows the three simulation cases that will be compared in this work for the validation of the present model.

Table 2. Geometrical parameters of the pipe.

Pipe lenght [m]	4.336 (167D)	Virtual probe #3 [m]	0.988 (38D)
1st section lenght [m]	0.936 (36D)	Virtual probe #4 [m]	2.028 (78D)
2nd section lenght [m]	3.4 (131D)	Wake coefficient [a_w]	0.4
Virtual probe #1 [m]	0	Wake coefficient [b_w]	1.0
Virtual probe #2 [m]	0.884 (34D)	Liquid density [kg/m^3]	999

Table 3. Entrance data for the simulations.

Simulation	1st section inclination angle	2nd section inclination angle	Mean liquid superficial velocity [m/s]	Mean gas superficial velocity [m/s]
1	Horizontal	3°	0.5	0.37
2	Horizontal	5°	0.5	0.38
3	Horizontal	7°	0.5	0.27

Since the model uses a lagrangian reference system, tracking down one unit cell along the pipe and saving its time-dependent parameters generates a typical output data set that can be obtained with the model. However, this type of data represents the behaviour of one single unit cell, which can be quite different from the mean behaviour of the flow due to the intermittence of the phenomenon. The slug length may show wide variations from one unit cell that coalesces during the simulation to another one that does not. Thus, it is common to show the output data as an average of all the unit cells for each virtual probe delimited at the beginning of the simulation and plotting it along the pipe (Rodrigues, 2009).

As the mean parameters do not show the intermittence of the phenomena, such as the variation of the slug length in each section of the pipe with time – an important facility design parameter – it is important to show the Probability Density Function (PDF) of the analyzed parameters. The mean value chart represents the flow behaviour along the pipe while the PDF represents the behaviour of the analyzed parameters in one point of the pipe along all the simulation time. These two types of output data are analyzed together in the present work.

The main slug flow parameters analyzed in this work are the slug length and the gas velocity in the bubble. The first parameter is the one that the present work has shown how to calculate during the unit cell passage through the elbow. The second parameter is the main parameter that changes due to the gravitational force in the inclined section and is known as one of the parameters that most affects the flow behaviour (Conte *et al.* 2011). The phase fraction variation due to the pipe direction was not examined due to the lack of experimental data.

Slug length behaviour

Figure 3 shows the mean dimensionless slug lengths for 3°, 5° and 7° along the pipe. For the 3° simulation, slug grows in the elbow due to liquid accumulation, and simulated and experimental data show good agreement. The same trend was found for the 5° and the 7° simulations. The 7° simulation has the best agreement with the experimental data in the elbow.

Figure 4 shows the PDFs for the three simulations for the probes downstream and upstream the elbow, which are the most important probes in the present work analysis. It can be observed that the elbow affects the shape of the PDF. For the 3° simulation, the PDF mode is the most dissimilar of the three simulations, showing that for such small angles the model does not capture the direction change phenomenon reasonably well. For the 5° and 7° simulations, even if the mode is slightly different, the area covered by the experimental and the simulated PDFs are close, showing a good agreement between them. They also showed similar peaks and standard deviations.

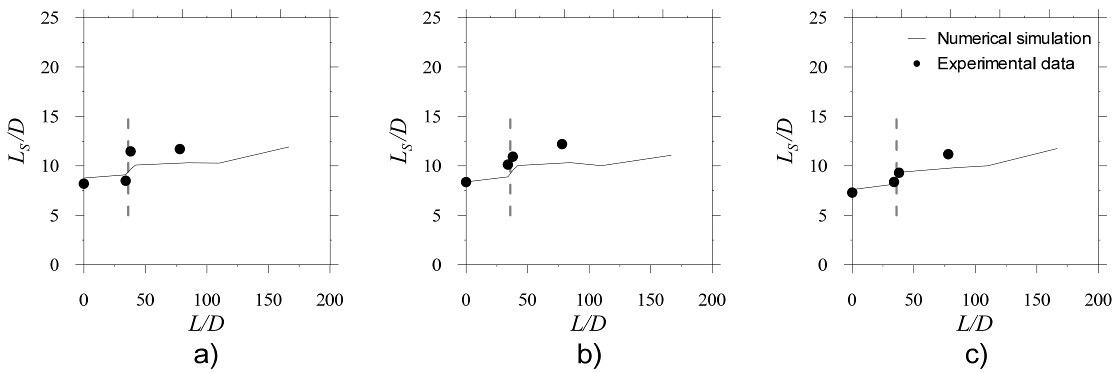

Figure 3. Mean slug length values for a) 3°, b) 5° and c) 7° plotted against experimental data.

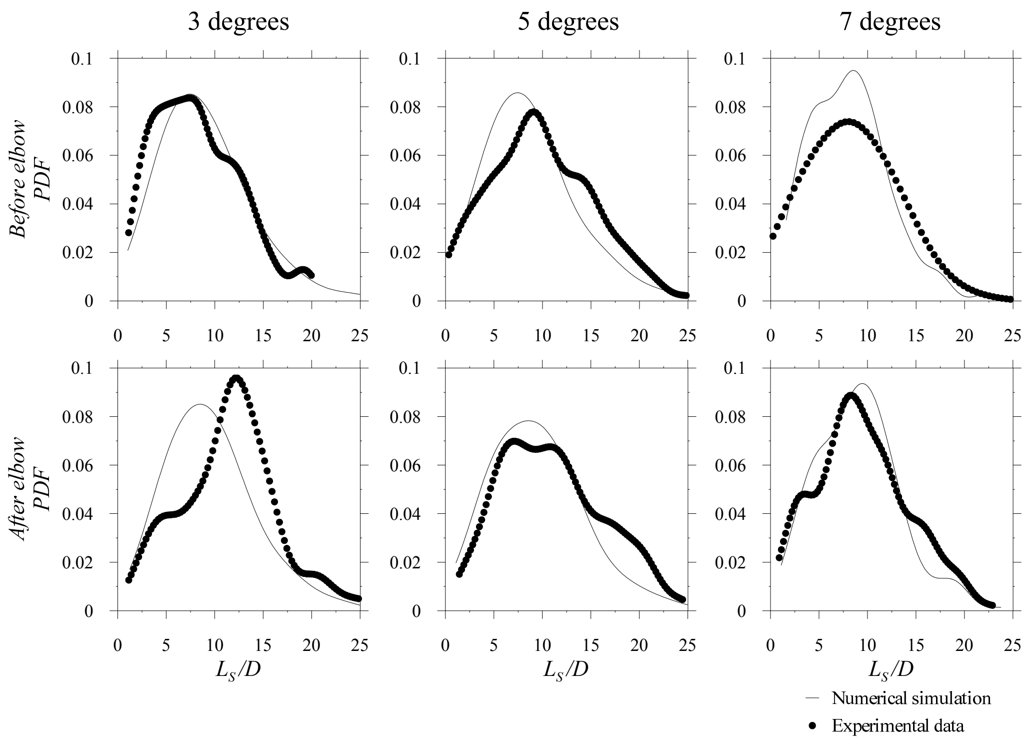

Figure 4. Slug length PDF before and after the elbow compared to experimental data.

Bubble velocity behaviour

Figure 5 shows the mean values of the gas velocity in the bubble. Experimental data indicate that the bubble velocity increases in the elbow due to the buoyancy force. The 3° simulation has underestimated this trend. This shows that the model does not capture bubble velocity changes for such small angles, according to the result of the slug length already shown. For the 5° and the 7° simulation, numerical results agree with the experimental findings.

Figure 6 shows the PDF for the bubble velocity. For all the three simulations, the PDF mode has been underestimated by the model compared to experimental data. For the 7° simulation, the peak and the standard deviation of the simulated data agree with the experiments and the shape of the PDFs are almost the same, nevertheless slightly displaced. It can be observed that, as the inclination angle decreases, the simulated PDF tends to decrease in height and spread, increasing its standard deviation.

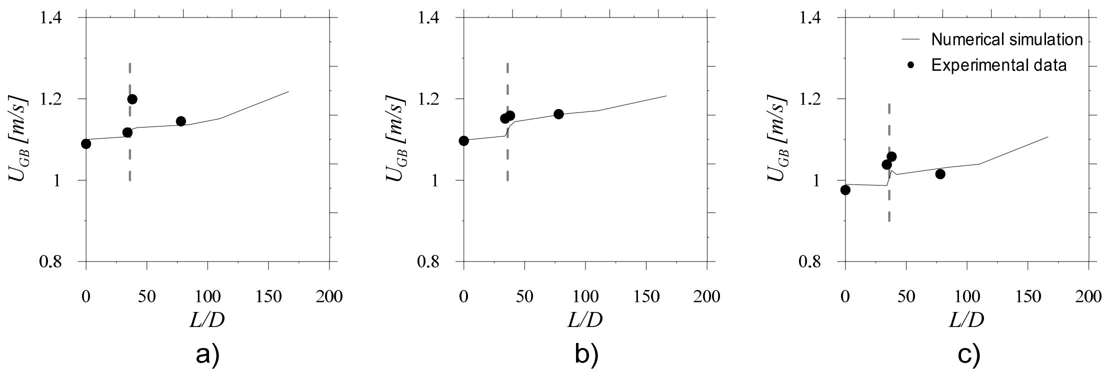

Figure 5. Mean bubble velocity values for a) 3°, b) 5° and c) 7° plotted against experimental data.

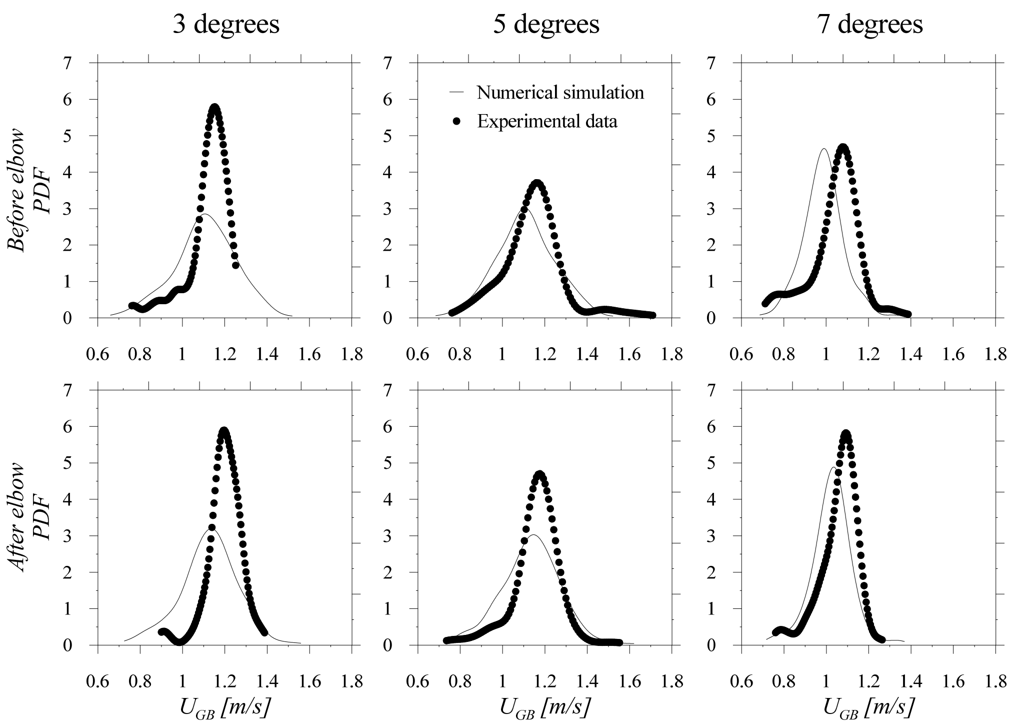

Figure 6. Bubble velocity PDF before and after the elbow compared to experimental data.

5. CONCLUSIONS

A mathematical model for slug flow simulation with slight direction changes was developed. The present work modelled two hilly terrain phenomena, the liquid accumulation in the low elbow due to gravity and the phase fraction changes due to acceleration of the elongated bubble, with gas release as small bubbles to the preceding liquid slug. The proposed model was coupled with the Rodrigues (2009) slug tracking model. The equations were discretized in time using the semi-implicit Crank-Nicholson scheme and arranged to form a system that solves pressure and slug velocities.

Simulations were compared to experimental data obtained in UTFPR/LACIT and a good agreement was obtained. Three simulations to compare the mean values and the PDF's of the slug length and the gas velocity in the bubble, considering 3°, 5° and 7° for the inclined section, were carried out. The slug grows in the elbow due to liquid accumulation. The model showed a better prediction for the 7° simulation. For small inclination angles such as 3°, the proposed model does not capture the phenomena fairly well. The PDF's shapes showed a good agreement for the slug length, showing that the model captures the intermittence of the phenomenon.

The gas velocity in the bubble increases in the elbow too, due to the buoyancy force in the inclined section. The bubble velocity simulated PDFs showed a flatten shape against the experimental data for the smaller angles simulation, with lower peaks and higher standard deviations. The model has underestimated the mean values of the bubble velocity in all the simulations. The better result was once again found for the 7° simulation.

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7. RESPONSIBILITY NOTICE

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